DOI:
10.1109/ACCESS.2020.2979135

IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received February 8, 2020, accepted February 17, 2020, date of publication March 6, 2020, date of current version March 23, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2979135

Applying Blockchain Technology for User Incentivization in mmWave-Based Mesh Networks

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This work was supported in part by the Academy of Finland under Project RADIANT, in part by the project 5G-FORCE, and in part by the RAAS Connectivity RTF Framework.

ABSTRACT Wireless traffic produced by modern mobile devices displays high temporal and spatial dynamics as users spontaneously engage in collective applications where a significant portion of generated data remains localized. As a result, conventional service provisioning approaches may no longer be sufficient in beyond fifth generation (B5G) systems. The challenge of increased dynamics on the access networks can be mitigated with moving cells. However, the deployment time of these temporary serving entities may lag behind the service demand lifetime. Another viable solution to offload excessive cellular traffic is to rely upon locally available radio resources offered by user devices via direct mmWave-based mesh interworking. An important challenge in such systems is related to the incentivization of users to partake in collaborative resource sharing. To leverage multi-hop mesh capabilities, we propose the use of emerging blockchain technology that offers cryptographically-strong accounting while maintaining the anonymity of the participants. With system-level evaluations, we demonstrate that the utilization of mobile blockchain methods allows for a non-incremental improvement in the offloading gains. This demonstrates the potential of the outlined proposal for becoming a successful mechanism in the emerging B5G systems.

INDEX TERMS Mesh networks, millimeter wave communication, blockchain, Ad hoc networks, 5G mobile communication, multimedia communication.

I. INTRODUCTION

Future mobile traffic is characterized by a high degree of temporal and spatial variations [1]. Today, these variations are becoming less predictable and often remain localized (the origins and the consumers of the content reside nearby), e.g., due to the growing popularity of proximate Augmented and Virtual Reality (AR/VR) services [2], [3]. This trend is expected to continue along with the deployment of millimeter-wave (mmWave)-based cellular technology, since Fifth-Generation (5G) New Radio (NR) access systems are likely to comprise relatively isolated bandwidth-rich islands [4]. Generally, the latest release of the 5G NR specifications is a significant milestone in the development of next-generation mobile cellular technology. By specifying the air interface that is capable of operating in the mmWave frequency bands and thus having the unprecedented capacity, 5G systems support bandwidth-hungry user applications, such as ultra-high-definition video streaming, AR/VR broadcasting, and proximate gaming [5].

Vendors and standardization bodies are currently working on a solution to alleviate the effects of spatial and temporal clustering of mobile traffic. The use of moving access points, e.g., cells-on-wheels [6] and aerial base stations [7], is considered promising in this context. Notably, 3rd Generation Partnership Project's (3GPP's) future Integrated Access and

The associate editor coordinating the review of this manuscript and approving it for publication was Theofanis P. Raptis.

Backhaul technology [8] is expected to provide improved access management, better route optimization, and higher spectral efficiency together with enhanced reliability. However, the utilization of this solution is featured by the deployment times on the order of tens of minutes, which may be prohibitive for many short-lived applications. Hence, efficient handling of spontaneous traffic bursts requires alternative approaches, which rely upon network resources that are available locally.

Spontaneous short-lived traffic can be offloaded onto direct device-to-device (D2D) connections [9]. The efficiency of such offloading depends heavily on the availability of content holders in close proximity as well as on their willingness to share the resources, e.g., paid cellular subscription and battery charge [10]–[12]. A natural extension of D2D communication is to construct on-demand mesh topologies, which can improve path diversity and thus reliability by utilizing multi-hop connectivity. Standardization bodies consider mesh topologies as an innovative response to future mobile demands: e.g., 3GPP expects to incorporate multi-hop relaying capabilities as a supplement to 5G NR, see TR 38.874 [8].

The efficiency of multi-hop D2D-based mesh topologies relies heavily on the willingness of users to share their resources in light of various concerns, including fairness, anonymity, and security [13]. If the participating users decide to leave the mesh overlay, this may severely impair the D2D network capabilities – the number of possible pathways to route excess traffic, the total internal and cellular capacity of the mesh, etc. Therefore, one of the crucial factors for improving the efficiency of localized traffic offloading is to employ an incentivization layer that stimulates users to share their resources in a multi-hop D2D mesh.

To this end, the works in [14] and [15] already indicated the potential of cooperative sharing in peer-to-peer (P2P) systems by utilizing game theory. One of the underlying drivers is the fact that the users may achieve savings because of the potential discount incentivization, so that the actual price to be paid for the use of the wireless/computational/storage resource can better match the actual value/interest that they assign to the service in terms of the energy/throughput/download cost as compared to incentiveless systems. Multiple studies looked into the performance of distributed network incentivization in beyond-5G systems [16]–[18], with the aim to improve the overall system- and user-centric experience by managing the available resources in a more efficient way.

For the D2D-based mesh, a blockchain-enabled overlay may potentially mitigate user concerns regarding the fairness of resource sharing by encouraging them to participate in collaborative networking. Such blockchain-incentivized mesh networks for localized traffic offloading are mutually beneficial for both system operators and their clients [19]. The clients will experience better service quality for the same price while also contributing to the operator's network coverage. In some scenarios, users may receive additional rewards from the operator for committing their resources. These rewards may be regarded as the operator's investment into the network offloading infrastructure. Indeed, from the operator's perspective, on-demand mesh topologies temporarily extend the availability of network services as well as enhance the resultant service quality without additional capital expenditures.

The main goal of this work is to outline an innovative blockchain-based technology that has a solid potential to be successful in the emerging 5G-grade mobile scenarios. To illustrate the said potential, we target an increase in the proportion of traffic to be offloaded onto a multi-hop D2D-based mesh by utilizing blockchain as an incentivization scheme for the end-user involvement. The numerical results of this study demonstrate that such blockchain-incentivized mesh overlays address the heavy traffic demand if the latter is localized spatially and temporally.

The rest of this text is organized as follows. In Section II, we offer a brief review of blockchain applications for wireless networking. Further, in Section III, we introduce the rationale for using blockchain to enhance the service provisioning in beyond-5G systems. The prospective benefits of blockchain-incentivized mesh overlays are illustrated in Section IV. The respective open issues and research challenges are discussed in Section V. Section VI concludes the paper.

II. APPLICATIONS OF BLOCKCHAIN IN COMMUNICATION

The introduction of the first blockchain-based technology, Bitcoin cryptocurrency, had a notable impact on our entire society. While cryptocurrencies have become an innovative alternative for the financial sector, behind them lays the fascinating concept of the blockchain. Owing to securely distributed ledgers that form the basis of the blockchain, applications that could only work previously via a trusted central node can now operate without it. This unique feature extends the application of blockchain far beyond the financial sector. Recently, various usages in wireless networking have emerged [20]. These key use cases are illustrated in Fig. 1 and can be categorized as: (i) machine-type applications; (ii) security and privacy features; (iii) communication technology enhancements; and (iv) user incentivization. Below we briefly address all of these.

A. INTERNET OF THINGS

The prospective Internet of Things (IoT) use cases serve as a natural application area for the blockchain technology [21]. The recent efforts in this field are focused on making IoT devices more autonomous [22]. Such devices must independently supply themselves with the necessary resources for extended lifetimes, better energy efficiency, and reliable wireless connectivity to achieve true autonomy. This challenge can be partially addressed by using advanced energy harvesting techniques, prepaid contracts with the Internet provider, etc., thus providing all the necessary resources in advance.

Such self-sufficiency of the devices is promised by blockchain-based smart contracts [20]. These digitally-signed

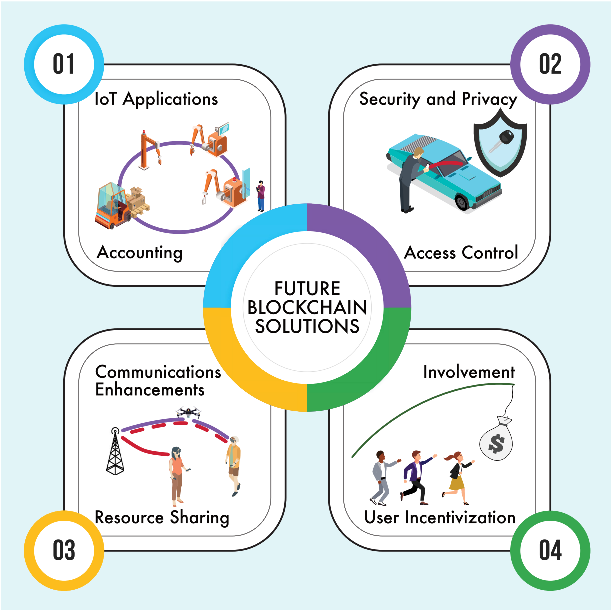

FIGURE 1. Various blockchain use cases in communications.

agreements specify the execution rules and enable the IoT devices to receive the necessary resources from other devices by offering them a specific form of commodity in return. For example, sensors can barter their measurements for electricity and Internet access. Hence, smart contracts create a new paradigm where IoT devices are equipped with trade relationships [23].

In addition to resource supplement, the blockchain–IoT coupling enables a mapping between the virtual and the real-world commodities. An example of this linkage is Slock.it and similar applications [20]. These can be used for opening locks and turning switches based on a blockchain transaction. Several solutions improve upon these basic functionalities. Many of them rely on the blockchain technology for autonomous smart manufacturing, i.e., on-demand access to manufacturing resources over a blockchain. Such use cases do not require a third-party intermediary for the client-to-factory communication, thereby substantially reducing the manufacturing overheads.

The use of blockchain in IoT is not limited to the scenarios considered here; there is a rapidly expanding body of literature and hundreds of blockchain start-ups. However, the utilization of blockchain in IoT is notably constrained by the resource-intensive procedures of consent and mining [24]. Existing lightweight solutions, such as private blockchain, do not support the "trust the untrustable" feature, in contrast to their public counterparts. There are, however, projects aiming to involve less computationally powerful devices in the blockchain operation [25] but those are in their early development stages. Therefore, optimizing blockchain for low-power IoT devices is a timely destination for research. When it is reached, the implementation options of blockchain in IoT will enhance significantly.

B. SECURITY AND PRIVACY FEATURES

The use of blockchain technology to address security and privacy challenges follows naturally from cryptocurrency use cases. Blockchain can be utilized as a tool for authentication and authorization, wherein the users may maintain the anonymity of their real-world identity and data privacy [26]. Theoretically, blockchain should adapt well to any application that requires timestamped and sequentially stored data. For example, modern healthcare employs electronic health records that are used for diagnosis and treatment. Altering those records may lead to incorrect assignments or fatal mistakes. In recent projects, blockchain was successfully applied to enhance unity and integrity of the health records [27].

Another example is in accessing permissions: the solution involves a smart contract that defines all of the operations allowed by the access control system for each user. This contract is unique and cannot be removed from the system maliciously. Such solutions offer reliable and secure access control, which can simplify rights management in applications with a large number of users [28]. Optionally, they can be extended for tracking devices or user/node activities [29]. The future evolution of blockchain-based applications for security and privacy is expected to partially replace the conventional systems when it comes to facilitating authentication, authorization, and accounting (AAA) [30].

C. COMMUNICATION TECHNOLOGY ENHANCEMENTS

The capabilities of contemporary radio networks can be enhanced through the blockchain technology for both users and operators [31], [32]. The use of smart contracts for managing subscriptions to telecommunication services is a straightforward example. By signing up, a smart contract subscriber may access roaming services at local prices. On the other hand, operators can attract more customers without additional investments into their network infrastructures (via more efficient utilization of the existing deployments), since affordable prices may encourage people to use cellular access instead of searching for free Wi-Fi service.

Another example is the use of blockchain in software-defined networks (SDNs) [33]. Since multiple operators may own SDN-based systems, it is challenging to provide the required levels of end-to-end service quality due to a lack of inter-network orchestration. Application of smart contracts enables automated negotiations between the SDN operators, thus efficiently addressing the problem.

A nascent area of blockchain utilization is resource sharing in communications. Networks and devices always operate under certain limitations, such as spectrum, energy, computation, and memory constraints. Certain applications or devices may not have the needed resources to perform a particular task, but the capabilities of other devices in the network are being utilized only partially at the same time. In this context, blockchain helps progress towards balanced and collaborative resource utilization between all the devices in a network.

Today, due to the steadily increasing demand for throughput in mobile wireless access, efficient bandwidth utilization techniques are required. Fixed frequency allocations are wasteful as the license holders do not employ their entire spectrum consistently [34]. Facilitated by blockchain, fixed frequency allocations can be replaced by dynamic spectrum trading, thus enabling more effective use of radio resources. However, blockchain-based resource sharing is not limited to spectrum. Multiple projects consider blockchain as a new enabler for computational resource sharing. The respective solutions may save power of the user device when conducting computationally expensive tasks.

To further improve the resource sharing capabilities, the resilience of blockchains to various attacks should be considered. Otherwise, freeloaders might employ the resources of other users without a compensation, and such systems will not be feasible.

D. USER INVOLVEMENT

Historically, incentivization played a central role in distributed systems, ever since the era of Napster and Gnutella back in the 90th [35]. Initially, the process of sharing content via point-to-point protocols was entirely free and organized in the barter (Tit-for-Tat) fashion. The higher upload rate one has, the better download rate one will experience afterward. Along these lines, the user was assumed to be fair – aiming to increase the corresponding utility function, e.g., bandwidth to upload. Considering the concept of first trying to upload the least available part(s) of a file to improve its availability, this makes for a powerful incentivization mechanism.

However, when the entire file is acquired and the user becomes a seeder, there is no need to remain a fair uploader anymore. This constitutes a significant problem, as the presence of seeders is essential for BitTorrent to operate effectively [36]. In the absence of another incentive to share the content, a seeder has no pragmatic motivation to keep a file available for others to download. A lack of reward and punishment can induce free-riders to such a degree that the system becomes inefficient [37]. Notably, after the TRON Foundation purchased BitTorrent, it was decided to incentivize the seeding users who receive their reward in Tronix (TRX) as they provide the content [38].

At the time of writing, TRX has already reached the top-10 of cryptocurrencies in CoinMarketCap, and the overall system operation was improved. The increasingly successful adoption of blockchain technology has confirmed that it has the potential to incentivize individuals involved in resource sharing. In academia, this approach is known as a Credit-Based Scheme [39], wherein the centralized authority initially provides or assigns certain virtual 'money' to each participating node, so that the nodes then utilize these tokens for the purposes of service exchange [40].

III. HARNESSING BLOCKCHAIN FOR ON-DEMAND MESH NETWORKING

In this section, we characterize the traffic demands in the forthcoming 5G NR systems and consider the opportunities to satisfy them. Then, we proceed by introducing our concept of a blockchain-incentivized mesh overlay that may efficiently handle spontaneous traffic surges.

A. EMERGING BEYOND-5G SERVICES

Traffic demands driven by advanced mobile applications have been increasing continuously along with the evolution of cellular technology. Today, we are entering the era of bandwidth-hungry services, such as AR/VR that need to be supported by 5G systems and beyond. The target of these is to deliver a fully immersive user experience in a variety of contexts. Many of such scenarios are aimed at providing extreme impressions without any real risks for the user. Such services employ ultra-high-quality video and sound, to achieve the said goals. According to recent evaluations, such services will require the bandwidth of up to 600 Mbit/s per user [41].

In 5G systems, those services can be considered within two representative contexts: (i) pre-planned deployments, such as stadiums [42], and (ii) spontaneous setups, such as multi-player AR/VR gaming. The first type of context is characterized by extreme densities and well-defined demands across time and space (a burst of traffic due to a public event, such as a football match). The number of participants, event duration, and type of content may also be known in advance; hence, the prospective network loading can be predicted. Such events typically occur in the designated areas with a dedicated network layout that satisfies the high traffic demands with dense infrastructure deployments.

The second context is spontaneous, as it is driven by localized interactions between the users (e.g., an AR game utilizing virtual and physical interactions of players in a particular location). Such events are initiated randomly and may lead to high spatial and temporal variations in network traffic. Hence, it is often challenging to predict the corresponding traffic demands imposed by such applications – and to provide timely network infrastructure support.

B. SERVING SPONTANEOUS DEMAND

To satisfy the extreme bandwidth requirements and mitigate the bottlenecks in cellular access, 3GPP was developing a novel 5G NR interface that may operate in the mmWave frequency bands. Communications in this band bring fundamentally new challenges, including limited coverage (up to 100-400 meters depending on the propagation environment) and blockage of the radio propagation path by small objects [43].

To address these challenges, 3GPP specifications support multiple simultaneous connections to the neighboring access points. However, sufficiently dense mmWave infrastructure required for such multiple connections is expected to only be available in dedicated locations with predictably high traffic loads, e.g., stadiums, squares, and transportation hubs. To support wireless connectivity in other places that observe spontaneous traffic variations, the community is currently considering the use of moving cells deployed on cars and drones.

However, the above approach has two significant limitations. First, the use of moving cells incurs additional maintenance and coordination costs, which increase both capital (CAPEX) and operating (OPEX) expenditures. Second, the deployment time of moving base stations is on the order of minutes, which might be comparable or even longer than the duration of the spontaneous event itself. Therefore, unpredictable traffic demand is difficult to accommodate even with the emerging 5G NR cellular systems.

An alternative approach to serving spontaneous short-lived events is offloading the localized traffic onto D2D connections. Similarly to existing Wi-Fi-/LTE-Direct D2D solutions [44], the intention is to incorporate the D2D functionality into 5G mmWave-based systems. Particularly, 3GPP has adopted Cyclic Prefix-Orthogonal Frequency Division Multiplexing (CP-OFDM) with a scalable numerology and self-contained integrated subframe design in both uplink and downlink to simplify the overall system implementation, especially with respect to D2D-based mesh topologies, see 3GPP TR 38.201 [45]. While D2D connectivity is beneficial for the overall network performance [46], the efficiency of resource reuse is reduced because today's D2D solutions are mostly limited to single-hop communication.

The poor utilization of local resources not only affects the path diversity gains but also becomes a hurdle for the prospective mmWave-based D2D technology, where link blockage events may lead to a temporary loss of connectivity [47]. Therefore, to support reliable proximity services each device needs to maintain multiple backup links and switch between them in the case of blockage. Hence, to fully exploit the capabilities of mmWave-based D2D technology, localized mesh overlays are essential. Moreover, the recent studies of Wi-Fi Direct and LTE Sidelink indicated that D2D communication is beneficial for the network performance [46], [48].

The emerging WiGig-/NR-based D2D technologies, together with 3GPP developments in relay systems, see 3GPP TR 38.874 [8], allow to construct such on-demand mesh layouts. Multi-hop communication below 6 GHz is long known to be limited by excessive interference under higher loads, which naturally constraints the efficient use of mesh networks. However, with the recent advent of systems operating in mmWave bands, the concept of mesh networking may be revisited Particularly, the prospective use of antenna arrays at both sides of a communication link may drastically improve the interference conditions, thus shifting the operating mode from interference- to noise-limited.

There are two key considerations to be met for enabling localized mesh overlays: (i) *efficient routing* (hundreds of users may attend a local event); and (ii) *user incentivization* to join the mesh and share the resources of personal devices. Mesh routing has been subject to active research for the last two decades. Resultant protocols utilize on-demand and table-driven solutions by complementing them with the use of external resources (e.g., GPS-assisted position-based routing) [49]. Several schemes employ directional antennas as well as enable the required scalability of mesh routing protocols based on logical address spaces. Finally, some protocols (e.g., Ad-hoc On-demand Distance Vector, AODV) inherently support multi-interface radio technology. In contrast, incentivized resource sharing in an on-demand mesh remains a pressing problem.

C. LEVERAGING BLOCKCHAIN CAPABILITIES

The primary challenge of user incentivization is related to the personal concerns and the potential risks associated with resource sharing: perceived unfair resource sharing process, privacy issues, and selfish user behavior. As a result, individuals may have a limited willingness to engage in collaborative resource sharing. Blockchain-based overlays deployed on top of a network mesh may alleviate these concerns by offering cryptographically robust AAA functionality. However, to efficiently utilize this technology in mesh wireless systems, it must meet the inherently heterogeneous computational capabilities of various devices. Compared to the conventional technologies (e.g., Bitcoin), the recently proposed blockchain solutions are considerably more resource-efficient thus aiming to process millions of transactions per second by utilizing light consensus algorithms and multi-level hierarchical architectures [50].

Original blockchain consensus algorithms relied on computationally intensive proof-of-work (PoW) methods. Contemporary blockchain solutions utilize the significantly less demanding proof-of-stake (PoS) approach. In PoS, processing nodes deposit stakes to guarantee their dependability and reach a consensus by using the Byzantine Fault Tolerant protocol. Such an approach is extremely lightweight and allows for faster transaction processing and better energy efficiency, which enables blockchain operation on computationally constrained devices (e.g., IoT electronics).

Another drawback of the conventional blockchains is that significant memory space is required for continuously growing ledgers (e.g., the size of Bitcoin blockchain in Q1 2019 is about 210,557 Mbytes), which prevents the technology use on resource-constrained devices, such as smartphones and wearable electronics. This problem can be mitigated by utilizing multi-level blockchain concept also referred to as *"blockchains of blockchains"*. Such a system is managed by the master blockchain on the top, which contains the general information about the protocol, the set of validators and their stakes, the set of currently active lower-level blockchains, and the set of hashes for their most recent blocks. Behind the master blockchain, there may be several levels of nested blockchains. While underlying blockchains may have different formats of account addresses and transactions, they all satisfy the set of interoperability criteria to enable interaction between different blockchains.

The multi-level blockchain architecture can be utilized for the considered dynamic mesh systems when serving spontaneous demands. The validation of blocks in the master blockchain is performed by operator-driven nodes that deposit considerable stakes in the system. Then, a smaller subset of validators is assigned to each blockchain of a lower level. Each validator may participate in several blockchains on the same or different levels. Hence, all validation and consensus algorithms may run in parallel. When the lower blockchain ceases to exist, the balance of nodes is stored in the blockchains of higher levels by ensuring that user balance is preserved over time. For instance, a temporary blockchain used for supporting the operation of a mesh network in a certain location can be considered as a block of the higher-level blockchain.

The use of this multi-level approach brings the benefits of distributed ledgers to the constrained devices and incentivizes users to share resources by providing (i) a cryptographically strong accounting of the resources shared by each user, (ii) anonymity of the participants, and (iii) additional rewards from the operator for those users who share their resources.

IV. ILLUSTRATIVE INCENTIVIZATION SCENARIO

In this section, we introduce and numerically assess a representative scenario where a blockchain overlay provides the incentivization framework for traffic offloading onto the D2D-based mesh network. The proposed distributed security framework can allow for establishing trusted multi-hop relays for users in proximity. This, however, brings one significant challenge in the form of a question: *how should the users be incentivized to transfer the traffic of other users?*

A. RATIONALE FOR PROPOSAL

As one of the potential solutions for user incentivization, we propose to utilize dedicated tokens that could be either spent for a direct action (e.g., paying for the actual data being relayed) or used for other services. Generally, one may consider the initial allocation of tokens as part of the cellular operator contract. The users offering their resources perform the function of temporary (moving) base stations within the operator's network infrastructure as well as act as relays for direct connections of other users. Therefore, such sharing may be directly supported by the operator: a user benefiting from relaying spends x tokens, which are distributed between the involved k users. Here, each of these k nodes receives $x/k + \sigma$, where σ is an additional operator incentive. The latter can be regarded as an operator investment into the on-demand network infrastructure.

To provide practical grounds for the considered incentivization methodology, we interviewed 120 international students from two local universities regarding their acceptance of this relaying concept by using 5-scale Likert statements in an online survey (Disagree (1) – (5) Agree). The context offered to the interviewees was as follows. A user is connected to the cellular network but has an extremely low quality of service. However, he/she is willing to share the data with a person at the same university. At the moment, there is no way to reach the target recipient neither through Bluetooth nor via AirDrop due to limited coverage. However, there is another user located between those two, who can in principle relay the data in question. Assume that data transfers are entirely safe and private. Note that relaying will drain the battery.

The questionnaire contained the following questions: (1) Would you like to act as such a relay in case the infrastructure connection quality is low? (2) Would you like to do it if you can use someone as a relay for your transfer? (3) Would you like to do it if you will be rewarded by some token from the user who is requesting help? Most of the respondents think positively about relaying their data through other smartphones in case of a poor cellular connection (median (MED) – 4, standard deviation (SD) – 1.22). In general, they have a neutral attitude regarding their smartphone being used as a relay to transfer such data (MED – 3, SD – 1.2). However, the opinion of the majority changes to positive if they are offered a reward from a user who requests relaying service (MED – 4, SD – 1.08). These findings confirm that the utilization of additional operator OPEX may indeed shift the attitude of mobile users towards sharing their resources.

TABLE 1. Core simulation settings.

System parameter	Value
Operating frequency	28 GHz
Bandwidth	2.0 GHz
AP transmit power	2.0 W
UE transmit power	0.2 W
UE antenna array	16 × 16 elements (planar array)
AP antenna array	128 × 128 elements (planar array)
Propagation model	3D 3GPP outdoor cluster model
Blockage attenuation	20 dB
Symmetric connection load	400 Mbps
Cell size	100 x 100 m
Maximum mesh hop range	3
Mobility model	Levy flight (with parameter 1.5)
Number of users	[10-100]
Incentivization parameter, α	[0; 0.3; 0.5; 0.8]
Number of executions per setup	10e5

B. REFERENCE SCENARIO

Further, a system-level performance assessment has been conducted by utilizing our custom-made simulation environment to quantify the benefits of the proposed concept. The main modeling parameters are provided in Table 1. Our reference setup recreates a dense metropolitan area fully covered by the conventional cellular technology (3GPP LTE) and partly served by mmWave-based 5G NR. The total capacity of the mobile access network is lower than the aggregate user demand within a cell. The users move freely across the area of interest according to the Levy flight mobility pattern.

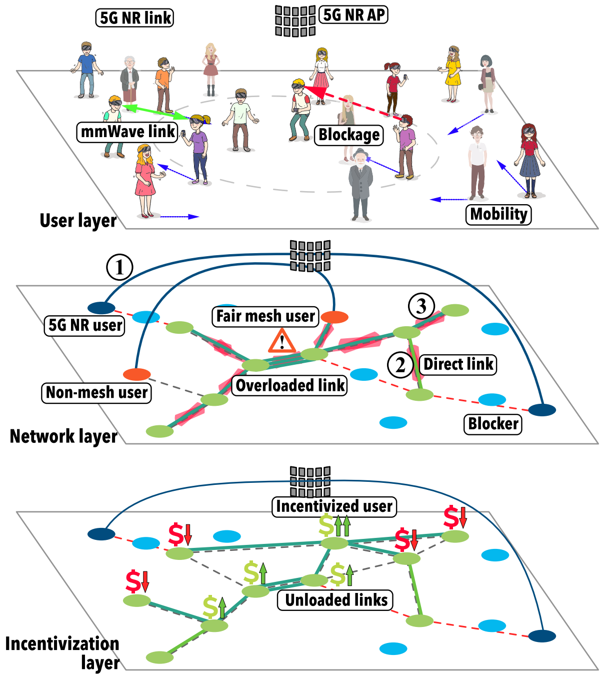

FIGURE 2. Considered use case: proximate AR/VR gaming.

We assume that the user traffic is produced by AR/VR multi-player gaming where the highest user density corresponds to the situation of comfortable playing.

The signaling of the D2D-based mesh (discovery and connection setup functions) is facilitated by the LTE coverage, whereas data transfers between the nodes of the mesh are performed over mmWave links. Such links may be affected by blockage due to moving obstacles. We estimate the blockage probability for each link according to [51]. In summary, Fig. 2 demonstrates the three planes of system operation. In our scenario, the users may exhibit different behavior based on their incentivization level: (i) willing to act as a relay all the time; (ii) willing to act only with a certain probability; (iii) not willing to relay but aiming to consume cellular resources. We compare the following alternative options:

- **Baseline Cellular Solution.** In this case, network connectivity is only available over the cellular links, without any D2D-based mesh support.
- **Standard Cellular–Mesh Solution.** Users have an option of establishing multi-hop communication if their selected partner cannot connect directly. If any intermediate link is overloaded, the current session is routed via the cellular network, whenever its radio resources are sufficient. If not, the session is dropped and a link reestablishment procedure is triggered immediately. The willingness to assist others (the incentivization parameter α) is set to 0.3 based on our survey, but no reward is provided.
- **Incentivized Cellular–Mesh Solution.** In this scenario, the operator offers an additional reward to each relaying node that participates in offloading. At the same time, users utilizing the relaying service pay tokens to their helpers. To highlight the effects of the incentivization layer, we consider different values of α: 0.5 and 0.8.

The metrics of our performance evaluation campaign are: (i) aggregate effective throughput, which is the data rate made available by using both cellular and mesh networks; (ii) ongoing session drop probability; and (iii) operator's OPEX represented as the number of tokens provided by the operator to incentivize the relay nodes.

C. ILLUSTRATIVE RESULTS

To familiarize the reader with the proposed concept, we also developed a simple yet representative visualization of the system lifetime, from the instant of network initialization to the stable operation phase. The corresponding representation is offered in Fig. 3, which is a sketch of the randomly distributed and numbered nodes within the area of interest. In this scenario, we fixed the positions of nodes for a better representation of the network operation. The links between the nodes correspond to the established mesh connectivity, where the nodes without any links are utilizing infrastructure-based communication or do not use it at all.

Fig. 3 ① depicts the instant of the mesh construction, where each node has an equal radius since no incentivization occurred yet. Further, during the system operation time, certain nodes are becoming involved into the mesh system operation more actively by offering their resources more intensively; hence, their stake is growing. Fig. 3 ② represents this scenario, where some nodes have already achieved better rewards, which are represented with the circles of a greater radius. The connectivity load corresponds to the link width. Fig. 3 ③ displays the system state after a relatively long operating time. Importantly, the nodes may have a small stake but their links are heavily employed, which may be due to their own active utilization of the neighboring links, thus resulting in the need for own spending.

To show the actual incentivization effect of the blockchain technology, we first demonstrate the mean number of nodes involved in relaying, see Fig. 4. This evaluation is based on the survey results reported in subsection IV-A. As one may observe, when α – that specifies the involvement of the blockchain – increases, the number of nodes involved in relaying first grows linearly with the number of nodes in the network. The underlying reason is that higher numbers of nodes increase the path diversity in the network as one may further observe in Fig. 5 that illustrates the number of connections in the mesh network. Hence, one may expect that higher values of α should positively affect the network capacity.

An increase in the number of relays incentivized by the blockchain facilitates new routes in the mesh, as indicated in Fig. 5, which results in more efficient traffic offloading onto the mesh network, and increases the aggregate system throughput (cellular and D2D-based mesh networks), consequently, as demonstrated in Fig. 6. In contrast to microwave

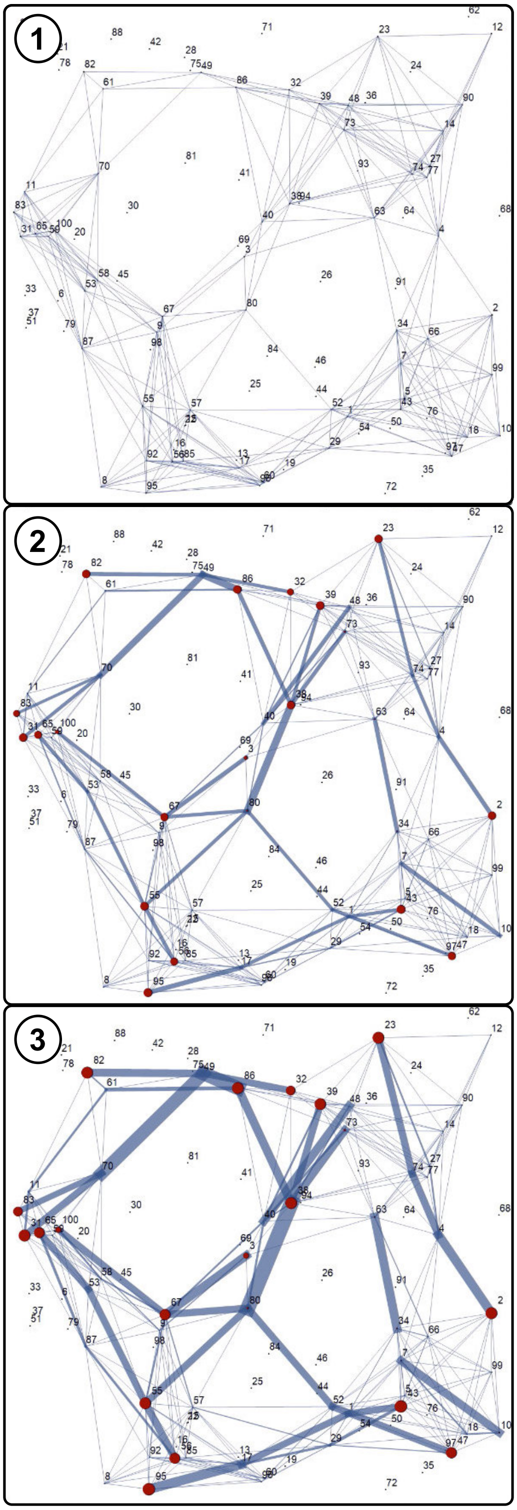

FIGURE 3. Blockchain-incentivized system lifetime.

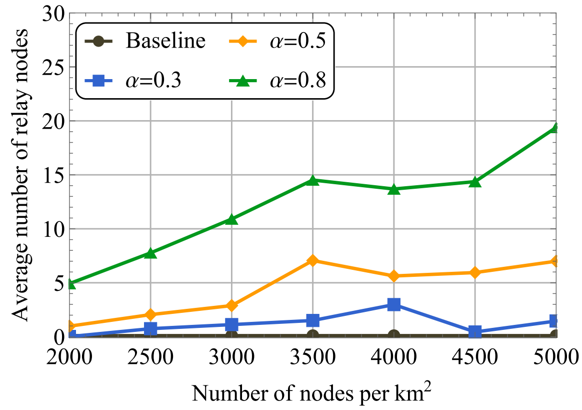

FIGURE 4. Average number of relay nodes.

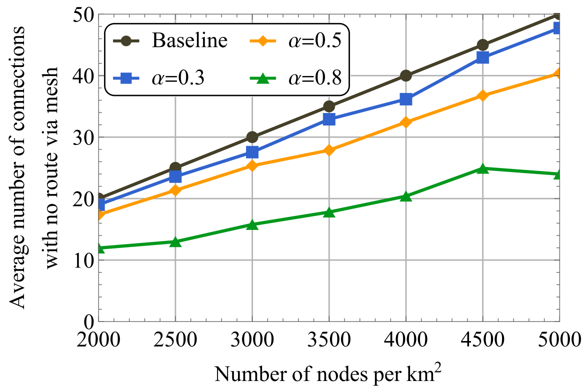

FIGURE 5. Average number of connections with no route via mesh.

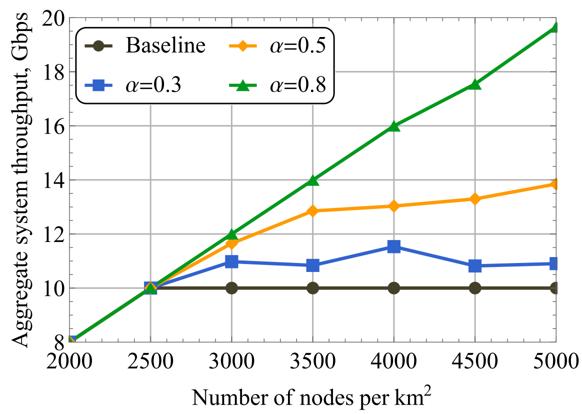

FIGURE 6. Impact of user incentivization on aggregate system throughput.

D2D technologies, in the proposed mmWave-based mesh, the users also benefit from significantly reduced interference. In particular, having 16×16 antenna arrays leads to approximately 6.5° half-power beamwidth (HBPW) at both transmit and receive ends. As a result, an increase in the mesh connection density does not drastically impact the link data rates for this class of scenarios.

As one may observe, in the baseline scenario, all of the users rely upon cellular infrastructure, which quickly becomes saturated as the number of consumers increases. At this loading level, the ongoing session drop probability begins to grow as further highlighted in Fig. 7. Increasing the incentivization parameter attracts more relays by improving the path diversity, and more traffic is thus being

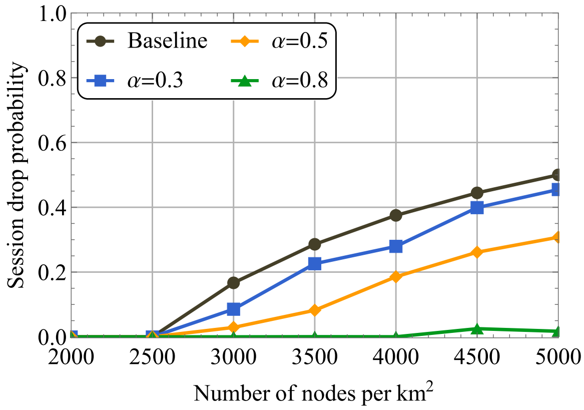

FIGURE 7. Ongoing session drop probability.

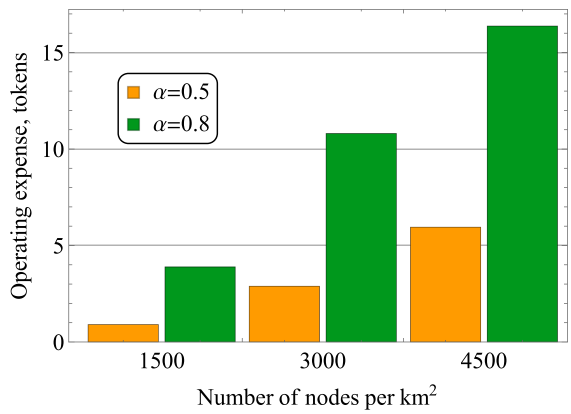

FIGURE 8. Mean operator OPEX for user incentivization.

routed through the mesh overlay. This effectively offloads the cellular infrastructure as well as decreases the ongoing session drop probability. In absolute numbers, the session drop probability decreases by approximately 0.45 when using highly incentivized overlays with $\alpha = 0.8$ as compared to the cellular infrastructure with $\alpha = 0.0$. The corresponding increase in throughput is approximately double.

Further, to characterize the OPEX controlled by the operator, we assess the average surplus of a node involved in the D2D-based mesh, as demonstrated in Fig. 8. One may observe that for the chosen system parameters, the mean system OPEX evolves similarly to the average volume of the aggregate traffic transferred by the integrated cellular–mesh system. A service operator might consider these expenses as part of OPEX by replacing its CAPEX related to the network infrastructure in those locations where the user demand surges are infrequent but harmful.

V. OPEN PROBLEMS AND CHALLENGES

The use of blockchain technology for incentivization purposes is an emerging concept with high potential. However, the inherent properties of its distributed operation may profoundly affect the efficiency of practical implementations. Below, we briefly outline the main open problems and challenges.

A. BLOCKCHAIN TYPE

One may envision two conceptually different flavors of the blockchain technology for incentivization purposes. Private blockchain solutions involve a single point of authority for joining the overlay and thus need to be established by the operator. This approach requires additional inter-operator interfaces to align their actions and strategies. Alternatively, the use of public blockchain schemes may potentially provide operator-independent functionality, while still ensuring that the operator participates in the overlay construction as a regular node.

B. DEVICE HETEROGENEITY

In mobile blockchain systems, nodes may have very different resources, which includes computational capabilities, battery budgets, etc. Here, the use of the conventional PoW consensus algorithms may lead to significant delays in confirming the transactions since some of the nodes may severely lag behind when performing the required calculations. Furthermore, computationally intensive algorithms (such as PoW) may unequally affect the battery lifetimes of the nodes. Therefore, to efficiently implement the blockchain technology, prospective systems may either require new lightweight schemes or use different consensus algorithms that intelligently assign computational jobs to a subset of carefully chosen nodes.

C. RESILIENCE TO ATTACKS

In conventional use cases, the resilience of blockchain to various attacks is ensured either by the size of the system itself (public blockchain), by a single authority (private blockchain), or, preferably, by a group of authorities (federated blockchain). A widely known attack on public blockchain solutions, which operate under the PoW consensus schemes, is a majority attack where a user having over 50% of computing power may create a malicious copy of the ledger. Since in a mobile system the number of participating nodes can vary with time, one needs to either (i) provide efficient means to alleviate the potential effects of these attacks (e.g., by implementing inherently persistent consensus algorithms) or (ii) introduce a certain level of centralized coordination (e.g., by using private blockchain).

D. INCENTIVIZATION STRATEGY

The emerging blockchain technology applied for user incentivization may or may not rely on the operator control. In the former case, the aspect of a surplus commodity is crucial for efficient incentivization. When an operator injects a commodity into the mesh overlay, incentivization is further improved by a possibility to exchange the earned commodity for additional services. The choice of commodity and its volume injected by the operator heavily affects the overlay performance via α factor, see Fig. 6, and is thus an important open research question.

E. INTEGRATION INTO 5G/5G+ LANDSCAPE

The proposed approach can be used as a tool for adaptive network management, in addition to moving cells. However, exploiting the full potential of the blockchain technology in 5G/5G+ networks requires additional standardization efforts related to new interfaces including signaling protocols and traffic accounting methodology with external incentivization systems. Primarily, standardization efforts are required to define terminology, signaling protocols, traffic accounting methodology, as well as specific aspects of the blockchain technology, e.g., consensus policy, mining procedures, and interoperability between the blockchains of different levels.

VI. CONCLUSION

In this work, we proposed the use of a blockchain-aided incentivization layer to improve the performance of future 5G/5G+ networks when serving bandwidth-hungry traffic generated by advanced AR/VR applications. Our results suggested that leveraging the blockchain-enabled incentivization technology on top of a mesh overlay allows to enhance cellular service by enabling effective traffic offloading. Furthermore, we demonstrated that the utilization of blockchain-incentivized D2D-based mesh topologies permits to overcome the inherent blockage phenomena in mmWave-based communication by providing with higher diversity of alternative data paths for prompt data rerouting.

Our numerical findings indicated that a mobile operator might control the performance of a blockchain-enabled mesh structure via the amount of commodity released for rewarding the users when sharing their resources. The higher rewards are offered, the more nodes are incentivized to participate in D2D-based mesh operation. Utilizing the radio resources allocated by the incentivized users, the operator may temporarily boost the capacity of its access network without extra capital expenditures. Hence, blockchain-aided mesh overlays can become a control plane element in future 5G/5G+ systems. They may also be included as part of future 3GPP specifications.

Finally, we identified open research issues and challenges related to the implementation of mobile blockchain technology. In particular, it has to offer effective means to combat the majority attacks as well as feature in-built algorithms that handle extreme heterogeneity of devices composing an overlay. We believe that blockchain's inherently secure operation along with its anonymization, cryptographically-strong accounting, and authorization capabilities will attract significant research attention to incentivized D2D-based mesh topologies.

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